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Comparison of photovoltaic nanogrid implementation: a simple reliability model for frontier, remote, and disadvantaged areas

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ABSTRACT

This paper aims to evaluate the photovoltaic (PV) nanogrid implementation and its risk for a project at a remote location. Unlike the normal approach, this approach is based on a discontinuity project. The main advantage of the model is the simplicity to compute the expected lifetime and display the reliability curve. The reliability is calculated using state space equation and a quantitative approach evaluates the risk of PV nanogrid scenarios based on costs. The MATLAB/Simulink simulates the scenarios including the basic scenario of a PV system that is a PV nanogrid consisting of a PV array and inverter, scenario 1 that is a PV nanogrid with a battery system, scenario 2 is an extension of scenario 1 with a battery repair, and scenario 3 is a PV nanogrid connected to the grid. The result indicates that adding a battery system increases the reliability and the expected lifetime of the system, and the battery system's maintenance makes it higher. Scenario 3 shows high reliability and a longer expected lifetime. The risk matrix shows the position of reliability and its impact on each scenario. This work can be used in practice as an objective assessment to electrify frontier, remote, and disadvantaged (3T) areas beside levelized cost of energy (LCOE).

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1. INTRODUCTION

Indonesia has reached 99.09% electrification [1]. The photovoltaic (PV) system benefits to supply the remaining location in frontier, remote, and disadvantaged (3T) areas. Indonesia has a target capacity of a PV system of 6.5 GW to be installed in 2025 [2]. A microgrid is a solution to electrify the areas. A microgrid exists in a variety of sizes and configurations, and can be connected to a grid or islanded mode [3]. International Renewable Energy Agency (IRENA) proposes grid categorization for picogrid, nanogrid, and microgrid [4]. Picogrid has a size of 0-1 kW with a single controller. Nanogrid has the size of 0-5 kW both grid-tied and remote systems, typically serving a single building or load with a single voltage. A microgrid has a power of 5-100 kW, where local energy supply and demand are manageable. Moreover, nanogrid are the solution to deliver of basic electricity services to people living in poverty [5].

The aplication of PV system includes solar home system [6] or hybrid system [7]. Levelized cost of energy (LCOE) is a standard tools used in evaluating a PV system [8]–[12]. However, when comparing the cost of different system, it had same year of lifetime [12] then it was assumed that it had continuous maintenance. Theristis and Papazoglou in [13] had modeled the reliability of a PV system during a sequence of failures accurately using the Markov process. Gbadamosi and Nwulu in [14] had developed an optimal power operation and reliability evaluation of a hybrid system for farming applications. When the penetration of microgrids increases, the need for operation and maintenance (O&M) services would create a new utility business model and yield higher grid reliability and resiliency. Utilities can offer O&M services to microgrid owners to guarantee reliable performance in the absence of an owner expert team. The maturity of business model operation and maintenance is low [3].

In addition, the PV system has a few problems in the implementation. Inverter in a PV system contributes to unscheduled maintenance [15]. Small domestic applications of a PV system are likely to suffer from low quality assurance, while in the UK it is around 96.6% [16]. Based on the data set of solar picogrid in rural northern India, the reliability of a household is around 2 outages per week over the one-year measurement period. The power outages are found due to a lack of produced energy caused by weather, technical breakups of system components, and unexpected user behaviour [17].

Futhermore, Nieuwenhout *et al.* in [18] had evaluated the finance types for solar home systems in the developing world. Donations have a problem with maintenance costs. Credit schemes are complicated when providing loans to rural communities. Cash sales are only accessible to the high-income community. Fee for service has an incentive to maintain the systems which benefit all parties [9].

Up to now, there are limited studies that compare the implementation of PV system and its risk. A risk-based approach has been considered to measure and identify the microgrid's resilience [3]. Risk assessment is comparing risk to the criteria that have been set. A semi-quantitative risk assessment needs complex data for electrical asset management. The application in electricity is the risk matrix from Canada and Netherlands [19], [20]. A quantitative approach of risk exists in API Recommended Practice (RP) 581 for fixed-pressure equipment from American Petroleum Institute (API) [21]. This paper proposes a simple model to compute the expected lifetime and display the reliability curve. This paper also proposes a risk matrix with a quantitative approach to compare the implementation of PV nanogrid based on reliability and its risk.

2. METHOD

Reliability is the probability that a component or system will perform the necessary functions under certain conditions for a specified period t [22]. Reliability of the system (R_S) is a sum of working states probability (P_j) [23]. The probability of failure (POF) is a complement of reliability.

$$\text{Reliability} = R_S = \sum_{j,working} P_j \tag{1}$$

$$\text{POF} = 1\text{- Reliability} \tag{2}$$

The expected lifetime of the system in [23] can be defined as in (3):

$$ExpectedLifetime = \int_0^{\infty} R_S \, dt \tag{3}$$

State space equation solve the scenarios reliability, as in (4):

$$\begin{aligned} \dot{x} &= Ax + Bu \\ y &= Cx + Du \end{aligned} \tag{4}$$

where x is the state vector of probability P_j, u is the input vector, y is the output vector P_j, $\dot{x}$ is the derivative of the state vector, A is the state matrix of the system, C is the identity matrix, and B and D is a zero matrix. Risk can be interpreted as an uncertain situation and harms a goal to be achieved.

Risk is defined as the product of probability and the consequences. The risk matrix shows the relationship between the probability of failure and the consequences of failure. Risk can be calculated using cost to measure the consequence of failure (COF). The consequences of failure are categorized as impact units consist of (a) small 0.1-1; (b) moderate 1-10; (c) significant 10-1000; (d) serious 100-1000; and (e) extreme > 1000 [23]. The COF category is calculated using a base cost of 1000 USD. The risk matrix in this paper is based on standard API RP 581. The risk is divided into low, medium, medium-high, and high [21]. The risk matrix is based on the risk category in Table 1.

$$\text{COF} = C_{eq} + C_r + C_m + C_{env} + C_{bi} \tag{5}$$

The financial consequences of COF are costs associated with failure to replace equipment, including equipment costs (C_{eq}), replacement costs (C_r), maintenance costs (C_m), business interruption costs (C_{bi}), and environmental costs (C_{env}). Equipment cost (C_{eq}) is the initial investment cost of equipment. Replacement cost (C_r) is the cost of replacing damaged equipment. Maintenance costs (C_m) are maintenance costs for equipment that fails. Maintenance costs amount to 2% of the investment value [12]. Environmental costs (C_{env}) are environmental impact costs. This cost equals 20% of operating costs [24]. The cost of business interruption (C_{bi}) is the financial loss when the system's operation is disrupted.

$$C_{bi} = T \times Q \times C_v \tag{6}$$

where T is the duration of time inoperative due to shut down, Q is the quantity normally produced, and C_v is the value of each production unit.

Table 1. Risk category

POF category	Range	COF category	Range (USD)
1	$0 \leq POF < 0.1$	A	$COF \leq 1000$
2	$0.1 \leq POF < 0.2$	B	$1000 < COF \leq 10.000$
3	$0.2 \leq POF < 0.3$	C	$10.000 < COF \leq 100.000$
4	$0.3 \leq POF < 0.5$	D	$100.000 < COF \leq 1.000.000$
5	$0.5 < POF \leq 1.0$	E	$COF > 1.000.000$

A PV nanogrid can be assembled by the PV array, battery system, solar charger controller, and inverter. A PV array consists of PV modules with two parallel units and two units in series forms to generate DC voltage from solar energy. An inverter is a power conditioning unit (PCU) to transform the DC output of the PV array into AC voltage. A battery system is energy storage to store or supply electricity, and it consists of two parallel units and two units in series forms. A solar charge controller is a component to control charging or discharging of the battery system. The parameters of components in Table 2 are from marketplace and existing literature [19], [25]–[33].

Table 2. Parameter of components

Component	Type	Capacity	Voltage (V)	Price (IDR)	Failure rate, λ (Failure per hour)	Repair rate, μ (Repair per hour)	Reference
PV module (PV)	SOL-P24250W	250 Wp	35.8	2,250,000	3.22320×10^{-6}	0.06670	[25], [26], [29]
Battery (BAT)	SOL12-100	100 Ah	12	2,600,000	1.47734×10^{-6}	0.04153	[31], [33]
Inverter (INV)	IP1500-22	1200 W	230	4,160,000	7.08668×10^{-6}	0.05731	[28], [33]
Solar charge controller (SCC)	Tracer4210N	1040 W	24	2,200,000	4.45673×10^{-6}	0.13405	[30], [33]
Transformer (TRF)	Oil immersed	400 kVA	400	105,000,000	7.0776×10^{-7}	0.00281	[32], [33]

A single point of failure (SPOF) is one component or function that causes the entire system to fail. The definition of failure for the system depends on how the service level agreement (SLA) had been defined. This paper evaluates how the electricity project was deployed and compare it to a basic scenario. The implementation scenario can be seen in Figures 1(a)-(c). The basic scenario was a PV nanogrid deployed without maintenance and it only had a PV array and inverter to supply load in the afternoon. It was designed usually for water pump application in the farming. The state matrix of basic scenario is

$$A = \begin{bmatrix} -(n_{inv}\lambda_{INV} + n_{pv}\lambda_{PV}) & 0 \\ (n_{inv}\lambda_{INV} + n_{pv}\lambda_{PV}) & 0 \end{bmatrix}$$

Scenario 1 was a PV nanogrid with a battery system but without maintenance. In addition to the basic scenario, it had a battery system and a solar charge controller. This scenario was designed typically to supply electricity in a rural area or on an isolated island. The state matrix of Scenario 1 is

$$A = \begin{bmatrix} -(n_{INV}\lambda_{INV} + n_{SCC}\lambda_{SCC} + n_{PV}\lambda_{PV} + n_{BAT}\lambda_{BAT}) & 0 & 0 & 0 \\ n_{PV}\lambda_{PV} & -(n_{INV}\lambda_{INV} + n_{SCC}\lambda_{SCC} + n_{BAT}\lambda_{BAT}) & 0 & 0 \\ n_{BAT}\lambda_{BAT} & 0 & -(n_{INV}\lambda_{INV} + n_{SCC}\lambda_{SCC} + n_{PV}\lambda_{PV}) & 0 \\ (n_{INV}\lambda_{INV} + n_{SCC}\lambda_{SCC}) & (n_{INV}\lambda_{INV} + n_{SCC}\lambda_{SCC} + n_{BAT}\lambda_{BAT}) & (n_{INV}\lambda_{INV} + n_{SCC}\lambda_{SCC} + n_{PV}\lambda_{PV}) & 0 \end{bmatrix}$$

Scenario 2 was a PV nanogrid with a battery system and proper battery maintenance. Scenario 2 had battery repair to scenario 1. This scenario was designed usually to maintain the system with the community's support. It had been quantified by adding a repair rate to the system to measure the maintenance factors. The state matrix of Scenario 2 is

$$A=\begin{bmatrix} -\left(n_{INV}\lambda_{INV}+n_{SCC}\lambda_{SCC}+n_{PV}\lambda_{PV}+n_{BAT}\lambda_{BAT}\right) & 0 & n_{BAT}\mu_{BAT} & 0 \\ n_{PV}\lambda_{PV} & -\left(n_{INV}\lambda_{INV}+n_{SCC}\lambda_{SCC}+n_{BAT}\lambda_{BAT}\right) & 0 & 0 \\ n_{BAT}\lambda_{BAT} & 0 & -\left(n_{INV}\lambda_{INV}+n_{SCC}\lambda_{SCC}+n_{PV}\lambda_{PV}+n_{BAT}\mu_{BAT}\right) & 0 \\ \left(n_{INV}\lambda_{INV}+n_{SCC}\lambda_{SCC}\right) & \left(n_{INV}\lambda_{INV}+n_{SCC}\lambda_{SCC}+n_{BAT}\lambda_{BAT}\right) & \left(n_{INV}\lambda_{INV}+n_{SCC}\lambda_{SCC}+n_{PV}\lambda_{PV}\right) & 0 \end{bmatrix}$$

Scenario 3 was a PV nanogrid connected to a utility grid through a transformer. Typically, this was the case where the resident builds a solar PV rooftop and was connected to a utility grid. Although, in this paper, the reliability had been seen from the residential load. The state matrix of Scenario 3 is

$$A=\begin{bmatrix} -(n_{INV}\lambda_{INV}+n_{PV}\lambda_{PV}+n_{TRF}\lambda_{TRF}) & 0 & n_{TRF}\mu_{TRF} & 0 \\ (n_{INV}\lambda_{INV}+n_{PV}\lambda_{PV}) & -(n_{TRF}\lambda_{TRF}) & 0 & 0 \\ n_{TRF}\lambda_{TRF} & 0 & -(n_{INV}\lambda_{INV}+n_{PV}\lambda_{PV}+n_{TRF}\mu_{TRF}) & 0 \\ 0 & n_{TRF}\lambda_{TRF} & (n_{INV}\lambda_{INV}+n_{PV}\lambda_{PV}) & 0 \end{bmatrix}$$

MATLAB/Simulink had been simulated all scenarios using (4) to display the reliability curve and expected lifetime. The risk had been calculated using a spreadsheet, where the impact had a log scale and the reliability had a proportional linear scale. The electricity price was 1444.7 IDR per kWh. The conversion was 1 USD equal to 14374 IDR. The risk per 1 year had been visualized using a risk matrix.

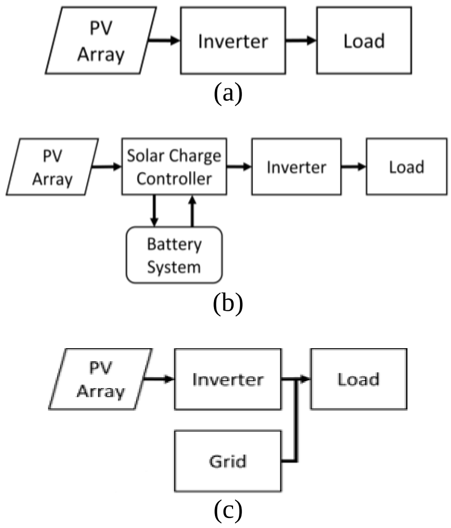

Figure 1. Implementation of PV nanogrid (a) basic scenario, (b) scenario 1 and 2, and (c) scenario 3

3. RESULTS AND DISCUSSION

3.1. Reliability evaluation

This simple model gain result fast and real time. A PV nanogrid in the basic scenario has an expected lifetime equal to 50,052 hours. Scenario 1 with a battery system increases the expected lifetime by 30.40%. Scenario 2, where the battery is repaired, increases the expected lifetime by 42.13%. Scenario 3, which is connected to a grid, increases the expected lifetime of the system by 2,822.16%. Details model dan result is shown in Figure 2.

Reliability curve is shown in Figure 3 to get more visualization of the system's reliability for a specified hours operation. The reliability of the system is compared in the third year due to the expected lifetime around 5.7 years. The reliability of the PV nanogrid is equal to 0.5915 in the third year. The battery system in scenario 1, the reliability increases by 0.7078, while in scenario 2, battery repair increases the system's reliability by 0.7217. The reliability of scenario 3 is increased by 0.9958, and it is the highest.

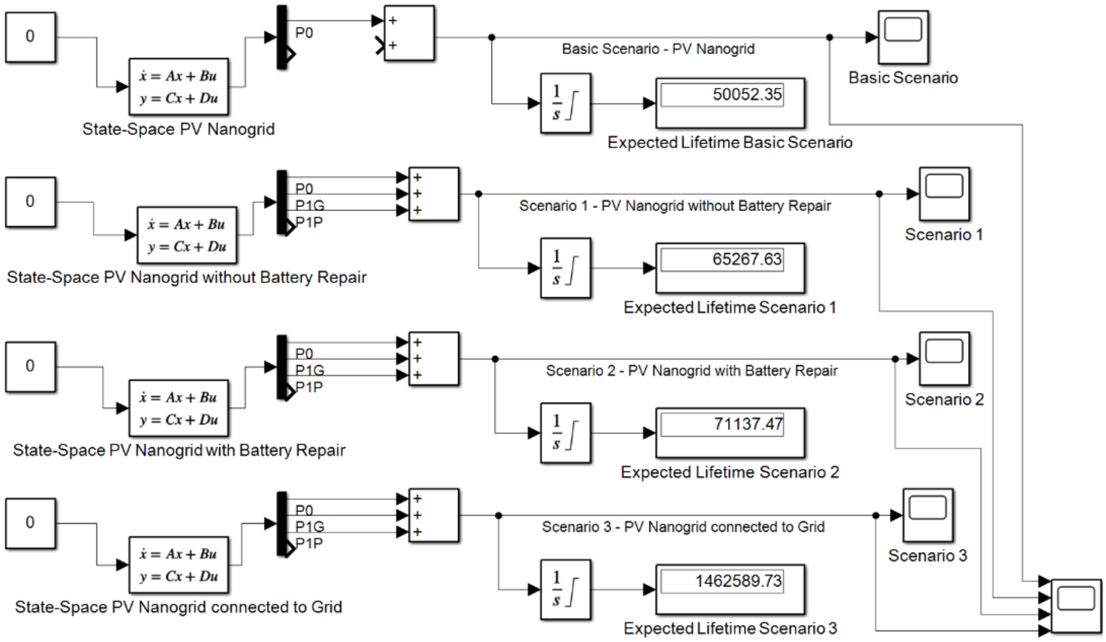

Figure 2. Comparison of PV nanogrid implementation using MATLAB/Simulink

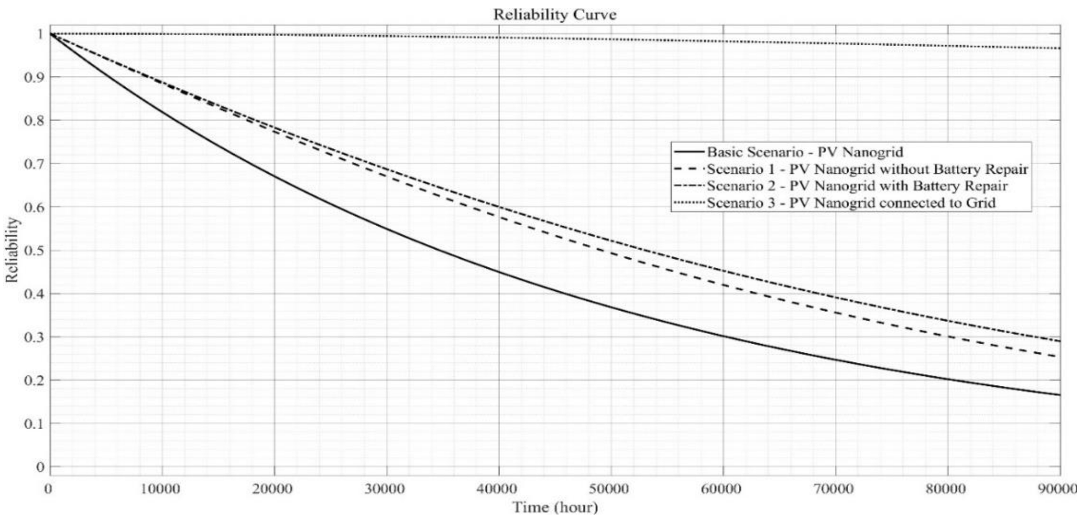

Figure 3. Reliability curve of PV nanogrid

3.2. Risk evaluation

The risk matrix shows evaluation results based on the probability of failure and cost-based consequences per year for a duration of five years. Decreasing system's reliability is indicated by an increased POF value. There are no additional costs in this duration due to discontinuity of the project.

PV nanogrid in a basic scenario has its risk moves quickly from low risk (2B) to medium-high risk (5B). In scenario 1, the risk per year moves from low risk (2B) to medium risk (4B). In scenario 1, adding a battery system lowers the probability of failure but increases the cost. Scenario 2 decrease the probability of failure but increase cost consequence as well. The risk of scenario 2 is lower than scenario 1 in the first year. Risk of scenario 2 moving from low risk (1B) to medium risk (4B). Scenario 3 has a low risk (1C) during these five years of calculation with the highest cost consequence. The risks of each system per one year can be seen in Figure 4.

The results are in line with previous study in [8] that have examined LCOE. Interestingly, the correlation between risk and LCOE is not as expected for scenario 2. The result is that adding battery system decrease the risk. In contrary, it increases LCOE.

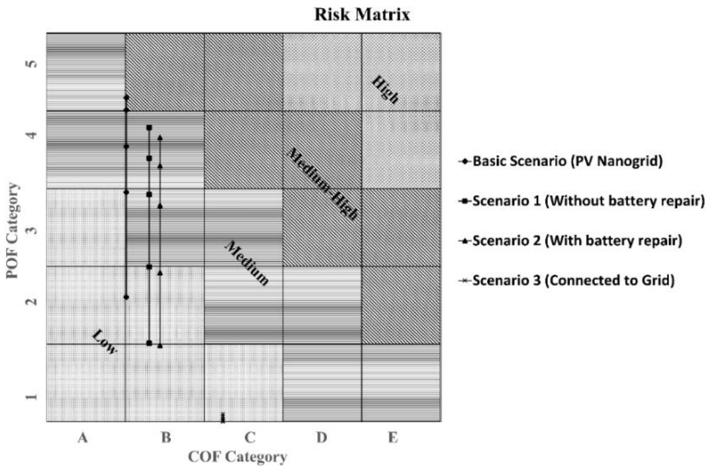

Figure 4. Risk matrix of PV nanogrid implementation

4. CONCLUSION

The aim of this study was to objectively measure and assess the PV nanogrid implementation and its risk for a project at a remote location based on a discontinuity project. This study has shown a simple model to compute the expected lifetime and display the reliability curve. The simulation has concluded that a battery system increases the system's reliability. The system's reliability is higher when battery maintenance is applied. The system's reliability is highest when PV nanogrid is connected to the utility grid. The risk matrix visualizes the quantitative evaluations based on the probability of failure and cost consequence of failure per year. Further research might explore the system risk movements that could be a reference in the maintenance planning.

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